GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2015), doi: 10.1111/gcbb.12296

Nitrogen rate and landscape impacts on life cycle energy use and emissions from switchgrass-derived ethanol

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Abstract

Switchgrass-derived ethanol has been proposed as an alternative to fossil fuels to improve sustainability of the US energy sector. In this study, life cycle analysis (LCA) was used to estimate the environmental benefits of this fuel. To better define the LCA environmental impacts associated with fertilization rates and farm-landscape topography, results from a controlled experiment were analyzed. Data from switchgrass plots planted in 2008, consistently managed with three nitrogen rates (0, 56, and 112 kg N ha^{-1}), two landscape positions (shoulder and footslope), and harvested annually (starting in 2009, the year after planting) through 2014 were used as input into the Greenhouse gases, Regulated Emissions and Energy use in transportation (GREET) model. Simulations determined nitrogen (N) rate and landscape impacts on the life cycle energy and emissions from switchgrass ethanol used in a passenger car as ethanol–gasoline blends (10% ethanol:E10, 85% ethanol:E85s). Results indicated that E85s may lead to lower fossil fuels use (58 to 77%), greenhouse gas (GHG) emissions (33 to 82%), and particulate matter (PM2.5) emissions (15 to 54%) in comparison with gasoline. However, volatile organic compounds (VOCs) and other criteria pollutants such as nitrogen oxides (NOx), particulate matter (PM10), and sulfur dioxides (SO_x) were higher for E85s than those from gasoline. Nitrogen rate above 56 kg N ha^{-1} yielded no increased biomass production benefits; but did increase (up to twofold) GHG, VOCs, and criteria pollutants. Lower blend (E10) results were closely similar to those from gasoline. The landscape topography also influenced life cycle impacts. Biomass grown at the footslope of fertilized plots led to higher switchgrass biomass yield, lower GHG, VOCs, and criteria pollutants in comparison with those at the shoulder position. Results also showed that replacing switchgrass before maximum stand life (10–20 years.) can further reduce the energy and emissions reduction benefits.

Keywords: bioethanol, Emissions, energy use, greenhouse gases regulated emissions and energy use in transportation, life cycle analysis, switchgrass

Received 18 March 2015; revised version received 9 July 2015 and accepted 15 July 2015

Introduction

Switchgrass (*Panicum virgatum* L.), a tall grass native to USA, is considered as a promising feedstock to produce second generation biofuel (McLaughlin & Kszos, 2005). Second generation biofuels (e.g., lignocellulosic ethanol) were mandated by US Energy Independence and Security Act of 2007 (Congress, 2007). Fueling millions of North American light duty vehicles with domestic cellulose-derived fuels could improve environmental quality and sustainability of the energy sector (Spatari *et al.*, 2005). Currently, major bio-ethanol feedstocks include corn (*Zea mays* L.) and sugar cane (*Saccharum officinarum* L.). However, biofuels production from row crops (e.g., corn starch-derived ethanol) may negatively impact water quality because nutrients transport from fertilized cropland can contribute to eutrophication of water bodies (Simpson *et al.*, 2008). It may also impact food security if croplands that feed humans are transformed into fuel-feedstock production lands (e.g., Naylor *et al.*, 2007; Simpson *et al.*, 2008).

Switchgrass, like many other tall grasses such as miscanthus (*Miscanthus giganteus*) and prairie cordgrass (*Spartina pectinata*), may be preferable in certain areas because it is perennial, can be grown on land less suitable for row crops, and can be used alternatively for forage. Its benefits include carbon sequestration, high

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biomass generation, and low fertilization and soil disturbance requirements (Wang *et al.*, 2010; Hartman *et al.*, 2011). Switchgrass production can be influenced by environmental conditions and agricultural management, especially in the first few years of establishment. Environmental conditions, such as landscape position, and fertilizer management can affect the biomass yield, greenhouse gas emissions, and eutrophication potential (Bai *et al.*, 2010; Nikièma *et al.*, 2011; Mbonimpa *et al.*, 2015).

One of the challenges of switchgrass production is that the yield and nutrients requirement depend on location, weather, and agricultural management (Parrish & Fike, 2005). To increase economic and environmental competitiveness of switchgrass-based biofuel, research has been focused on efficient feedstock production and biomass-to-fuel conversion. But there is still a wide range of yield potentials reported by various studies. Parrish & Fike (2005) indicated that in US regions with sufficient rainfall (e.g., US Midwest down to Southeast), roughly 15 Mg ha^{-1} of biomass can be produced annually with approximately 50 kg N ha^{-1} of fertilizer application. Guretzky *et al.* (2011) indicated yields of up to 21 Mg ha^{-1} in US southern great plains with N fertilization rate up to 225 kg N ha^{-1}. Nikièma *et al.* (2011) in Michigan observed yield increases from 4.89 Mg ha^{-1} with increases in fertilization of 56 kg N ha^{-1} (1.5× yield) and 112 kg N ha^{-1} (2.5× yield). Mulkey *et al.* (2006) reported that switchgrass biomass yield ranged from 3.5 to 5.5 Mg ha^{-1} in South Dakota with 56 kg N ha^{-1} of fertilizer, and no increase in biomass yield beyond this fertilization rate. These yields are achieved after full stand establishment. Switchgrass can take 1 to 3 years after planting to reach maximum yield potential (Parrish & Fike, 2005) and has a stand life of 10–20 years (Monti *et al.*, 2009; Sokhansanj *et al.*, 2009). The relationship between yield and N fertilization rate was found to be location dependent; switchgrass response to nitrogen is likely to be less pronounced in northern US locations than southern locations (Guretzky *et al.*, 2011). These yield–nitrogen relations may also vary depending on whether the management includes one or two harvests a year. One harvest could promote more carbon sequestration because, as suggested in Guretzky *et al.* (2011), it allows maximum translocation of nutrients and storage reserves in roots before harvest. In addition to N fertilizer, herbicides may be needed during establishment years; an established stand should outcompete weeds. Soil amendments such as phosphorus, lime and potassium may also be required (Bai *et al.*, 2010).

The yield and nitrogen management may also be influenced by the landscape topography, especially on sloped landscapes. In previous studies, greater biomass yields at the deposition position (footslope) were observed and linked to soils with greater production potential compared to higher elevation position (shoulder) (Bachman, 1997; Harmoney *et al.*, 2001). Higher carbon dioxide (CO_2) emissions and soil organic carbon were observed at the footslope compared to the shoulder position (Mbonimpa *et al.*, 2015). Carbon storage also varies with depth; Liebig *et al.* (2008) reported a significant carbon sequestration with soil carbon increases of about 1.1 and 2.9 Mg-C ha^{-1} year^{-1} for the 0–30 cm and 0–120 cm depths, respectively, when growing switchgrass.

To understand switchgrass and derived fuels, life cycle analysis (LCA), a common process for environmental accounting, has been used. Past LCA studies on switchgrass-derived ethanol generated inventories of environmental impacts from various life cycle steps that include switchgrass production (based mostly on yield for one or few locations), transportation, conversion of biomass to ethanol, transportation of ethanol, blending with other fuels, and use in various types of vehicles (Wu *et al.*, 2006; Bai *et al.*, 2010). This pathway is referred as well-to-wheel or cradle-to-grave to indicate start and end points of analysis. Usually to show the environmental benefits of the cellulosic ethanol and other renewable energy used in vehicles, the pathway of comparison involves petroleum-derived fuels such as gasoline (Wang *et al.*, 2012; Luk *et al.*, 2013). However, results from these LCA studies vary considerably due to differences in assumptions, inputs, and system boundaries. In particular, studies that ignored electricity coproduced from ethanol production process wastes (lignin) indicated less environmental benefits compared to studies that considered coproducts (Wang *et al.*, 2011; Luk *et al.*, 2013). Nevertheless, substantial environmental benefits of switchgrass-derived ethanol in comparison with fossil fuels were reported by previous life cycle studies. Spatari *et al.* (2005) indicated that greenhouse gas (GHG) emissions are 57% lower for a switchgrass-derived E85-fueled (85% ethanol, 15% gasoline) automobile compared to petroleum gasoline-fueled automobile. Wu *et al.* (2006) reported reductions in petroleum and fossil fuels (66–93%), GHG emissions (82–87%), and SOx (39–43%) when they compared switchgrass-derived unblended ethanol to gasoline. Schmer *et al.* (2008) reported 94% lower GHG emissions and 540% more renewable energy than non-renewable energy consumed during switchgrass ethanol life cycle (with switchgrass yield between 5.2 and 11 ton ha^{-1}) in comparison with gasoline life cycle. Bai *et al.* (2010) indicated that driving with switchgrass ethanol (E85) leads to 65% less GHG emissions than gasoline. They also noticed adverse impacts in comparison with gasoline. With 100 kg N ha^{-1} of fertilizer application, Bai

et al. (2010) calculated approximately 2.5 times more eutrophication potential (in terms of kilograms of PO_4 equivalent) in comparison with gasoline. Also, the addition of herbicides contributed to water ecotoxicity. However, the toxicity in Bai *et al.* (2010) may be overestimated because they applied herbicides every year, while in practice it is applied only in the first few (~2–3) years after planting switchgrass. They also did not clarify the impact management practices, such as fertilizer management, and location environmental aspects (e.g., soil, weather, and topography) have on their findings.

Although previous studies performed a complete LCA analysis for switchgrass-derived ethanol, most of them used the standard biomass yields, fertilizers rates, and included soil amendments which may not be needed at some locations. Most studies have not included field-scale agricultural conditions associated with nitrogen application rates and landscape positions which may influence the overall environmental impact of switchgrass-derived ethanol. To fill this gap, an LCA using the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Wang, 1999, 2008) was performed using data from a field-scale case study of switchgrass grown with different N application rates and landscape positions in US northern plains region. Data on specific energy used by machinery, soil GHG emissions under various treatment conditions, and biomass yield associated with N rates and landscape positions were used as inputs in the model. The primary objective of this study was to assess the impacts of field-scale agricultural management on the life cycle energy use and emissions of switchgrass-derived ethanol. Most vehicles currently on the road cannot operate on pure ethanol; therefore, this study focused on ethanol–gasoline blends as a realistic path forward for switchgrass-derived ethanol product development.

Materials and methods

System boundary and functional unit

The ethanol-blend life cycle was divided into three major steps: (i) the feedstock (switchgrass) production and delivery to the cellulosic ethanol production plant; (ii) the fuel production, mixing, and distribution; and (iii) vehicle operation. The production and disposal of machinery and vehicles are not included. The life cycle materials and processes are depicted in Fig. 1. Life cycle energy (Joules) and emissions (grams) were estimated per unit distance of vehicle operation (per kilometer). The feedstock production part of the study involved field experiments whereas fuel production and vehicle operation were accomplished using GREET model simulations (described later).

For the feedstock production, agricultural inputs including seed, nutrients, and herbicides were transported to the farm to grow switchgrass. The facilities that produce agricultural inputs acquired 75% of process energy from natural gas and 25% from electricity. The switchgrass production site was located near Bristol (45°16′24.55″N, 97°50′13.34″W), South Dakota, USA. The feedstock was produced on 12 plots (21.3 m wide and 366 m long each) that were historically seeded with soybeans (*Glycine max*. L.). Switchgrass was planted on May 17, 2008. The plots form a split plot factorial design comprised of three N treatments (0, 56, 112 kg N ha^{-1}) and two landscape positions (shoulder and footslope).

Fuel consumption of machinery for agricultural management activities was obtained from Grisso *et al.* (2004). The plots were not tilled before planting, and the switchgrass was planted using a ‘Truax no-till drill’ (Truax Company, New Hope, MN) pulled by a diesel-powered tractor. Herbicides were applied as needed from 2008-2011 using a diesel powered applicator.

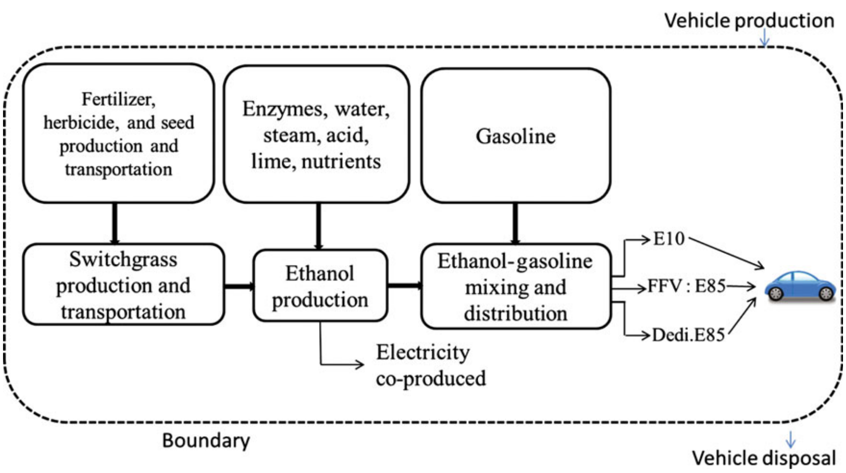

Fig. 1 Life cycle analysis system boundary for the study. Vehicle production and disposal were considered outside the scope of the study.

N was applied annually in late spring beginning in 2009 with the same type of equipment. Harvesting switchgrass started the year after planting (2009) and continued every year thereafter after a killling frost in autumn. Fertilizer continued to be applied each year in production years. Harvest was accomplished using a mower and baler pulled by a tractor. The farm activity of each machine was converted into energy inputs (Tables 1 and 2) using fuel consumed per unit area covered or per number of bales harvested. The switchgrass yield for each plot was calculated by weighing bales produced minus losses during transport and handling. The biomass yield at different landscapes was determined by sampling a square meter quadrat, mowing, and weighing for each landscape position. To account for moisture content, a subsample was collected, dried, and weighed. Soil GHG emissions from this switchgrass land were monitored as described in detail by Mbonimpa *et al.* (2015).

Life cycle inventory analysis and assessment using GREET model

The GREET (version1_2013) model developed by Argonne National Lab (ANL) was used for the LCA in this study (Wang, 1999). Fuels that were compared include gasoline, a mixture of 10% ethanol, and 90% gasoline by volume (E10) that can be used in most gasoline vehicles; and flex fuel a mixture of 85% ethanol and 15% gasoline by volume (E85) used for flex fuel vehicles (FFV). Total energy use, fossil energy use, petroleum use, GHG emissions, and emissions of criteria pollutants for a light duty passenger vehicle were obtained using GREET. This study compared the results from blended ethanol–gasoline technologies with those from gasoline. The technologies were assumed to be those available by the year 2015 (target year of simulations). Nitrous oxide (N_2O) emissions from switchgrass farming as a percentage of total nitrogen (N)-fertilizer were calculated from monitored N_2O emissions at various field experimental treatments, that is, fertilizer rate and landscape position (see Tables 1 and 2 for modeled scenarios). The simulations include potential CO_2 emissions reductions from land-use change that were estimated with Carbon Calculator for Land Use Change from Biofuel production (CCLUB) for the GREET model (Dunn *et al.*, 2014). The CO_2 reduction due to land-use change was estimated to be approximately 129 g L^{-1} of ethanol produced. GREET estimates a soil carbon sequestration of about 48 800 g CO_2 per dry ton of switchgrass.

Table 1 Farm-level information used in the GREET model for various N rates

	N levels		
Farm-level information	0 kg ha^{-1}	56 kg ha^{-1}	112 kg ha^{-1}
Moisture (average, %)	16.6	16.6	16.6
Yield (ton ha^{-1} yr^{-1})	3.74	5.11	5.12
Biomass (dry tons, d.ton ha^{-1} yr^{-1})	2.43	3.32	3.32
Fertilizer (g-N/d.ton)	0	13 126	26 226
Herbicides (g/d.ton)-15 year harvest	27.44	20.10	20.05
Farming energy (Btu/d.ton)-15 year harvest	174 401	151 679	151 531
Herbicides (g/d.ton)-1 year harvest	1365.6	998.8	997.8
Farming energy (Btu/d.ton)-1 year harvest	277 972	227 438	227 216
Seeds (kg ha^{-1})-sunburst variety	11.2	11.2	11.2
N content in biomass (%)	0.58	0.62	0.66
Harvest collection rate (%) (default-GREET)	90	90	90
N_2O* (% of N in fertilizer and biomass)	1.5	1.0	0.6

*Nitrous oxide.

Ethanol generation. The bioprocessing of switchgrass into ethanol was simulated using the GREET model as described in Wu *et al.* (2008, 2006), and they describe the source of emissions during the conversion processes. This process is a net producer (coproduction) of electricity (Spatari *et al.*, 2005). Ethanol yield used was 0.35 L kg^{-1} of dry biomass. This value (GREET (default value)) is based on assessment of recent conversion advances (saccharification/fermentation process).

Ethanol use. The GREET model vehicle fuel economy is adjusted for on-road performance using the US Environmental Protection Agency (EPA) kilometers-per-liter-based method and a split between city (43%) and highway (57%) vehicle kilometers traveled (VMT). In GREET (version1_2013), vehicle models are in 5-year increment; the target vehicle model in this study is 2010 with a fuel economy of 58 kilometers per liter. GREET also contains inventory of exhaust emissions (VOC, PM10, PM2.5, CH_4, and N_2O) in g km^{-1} traveled. Three types of alternative-fueled vehicles were compared with gasoline fueled. These include gasoline vehicles that consume low-percentage ethanol blends (E10), flex fuel vehicles (FFV, E85), and

Table 2 *Farm-level information used in GREET model for various landscape positions

Farm-level information	Landscape positions			
	Shoulder	Footslope	Shoulder	Footslope
N levels	0 kg ha^{-1}		112 kg ha^{-1}	
Biomass (Dry tons, d.ton ha^{-1} yr^{-1})	6.47	8.41	9.88	15.87
Fertilizer (g-N/d.ton)	0	0	8819	5498
Herbicides (g/d.ton)	10.26	7.89	6.72	4.18
Farming energy (Btu/d.ton)	65 496	59911	50 997	31 749

*These are the parameters that changed in reference to Table 1.

dedicated E85 (Dedi.E85) which are 6.5% more efficient than other vehicles (gasoline, E10, FFV).

Transportation and distribution. Switchgrass biomass was transported by heavy-duty trucks (25 metric tons of switchgrass payloads), and the ethanol produced is a distributed across country with barges, pipeline, rail road, and heavy-duty trucks. For the transportation, distribution distance values were obtained from GREET model default estimates. It was assumed that the switchgrass was transported to a conversion plant located at distance of 85 km one way (GREET model default).

Scenarios. A total of ten GREET models were setup and executed. Six models represented the three nitrogen rates (0, 56, 112 kg N ha^{-1}); each nitrogen rate had two models, one-year harvest or 15-year harvest. These two stand ages provided upper (full stand life, 15-year harvest.) and lower (abandonment, 1-year harvest) bounds. The resources used during stand establishment are distributed to years the switchgrass is harvested or abandoned. Four models represented shoulder and footslope positions; each position had two models, with no N (0 kg·N ha^{-1}) or high N (112 kg N ha^{-1}). These model scenarios contain different yields, energy use, biomass nitrogen content, N_2O emissions, herbicides to yield, and fertilizer to yield ratios as shown in Tables 1 and 2.

Results

Impact of nitrogen fertilizer and landscape position on energy use

The GREET simulations compared the total energy consumed during the life cycle of switchgrass ethanol blended with gasoline (used in three types of passenger vehicles: Std: E10, FFV:E85, and Dedi.E85) to that of conventional gasoline. Results (shown in Fig. 2) indicate that switchgrass-based blended ethanol life cycles may consume more energy (8 to 120%) than that of gasoline life cycle. However, gasoline life cycle

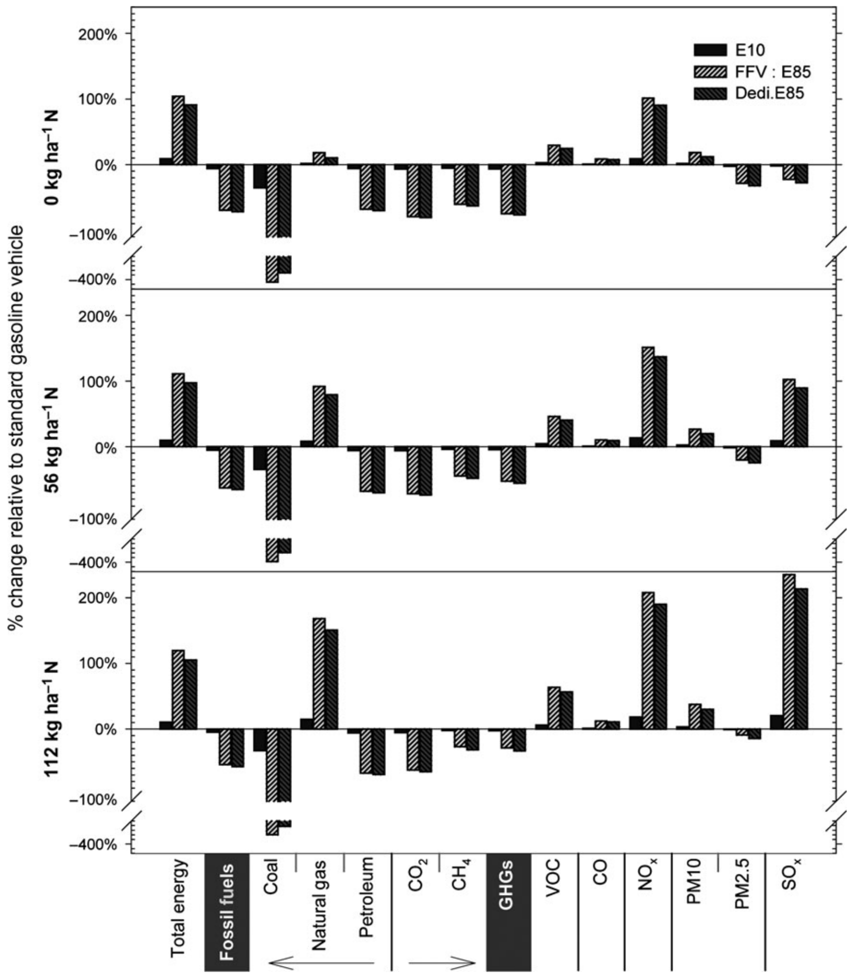

Fig. 2 Percent change of switchgrass ethanol life cycle impacts relative to gasoline for switchgrass grown with 0 kg ha^{-1} (top), 56 kg ha^{-1} (middle), and 112 kg ha^{-1} (bottom).

doi: 10.1111/gcbb.12296

uses more fossil energy (total of coal, petroleum, and natural gas) than blended ethanol's (E10, E85, Dedi.E85). Use of E85s resulted in 58 to 77% less fossil fuel consumption. E10 use reduced fossil fuels consumption by 5 to 6.5% in comparison with gasoline. Life cycle energy use by blended ethanol fuels was impacted by nitrogen (N) fertilizer applied during feedstock production (Table 3). The addition of 56 and 112 kg N ha of fertilizer increased total energy and fossil fuel use by 8 and 16%, respectively, in comparison with no N addition. The natural gas use increased with N fertilization rate increase as well (Fig. 2). The results also demonstrated a large saving in coal use (up to 406%) for switchgrass-based ethanol life cycle compared to gasoline in the Northern Plains region of United States (Fig. 2).

Further, the simulations showed that the landscape topography slightly impacted life cycle energy use. As shown in Fig. 3, when comparing ethanol blends and gasoline for the shoulder and footslope, the difference is small and less noticeable. On plots that received 112 kg N ha^{-1}, the shoulder position was linked to 88 and 94 kJ km^{-1} (approximately 5.4% of total energy) more life cycle energy use for FFV: E85 and Dedi.E85, respectively (Table 4). The difference was very small (~3 kJ km^{-1}) for plots where no fertilizer was applied. At low ethanol blend (E10), the difference due to landscape was also small (8 kJ km^{-1} at 112 kg N ha^{-1}, 0.28 kJ km^{-1} for no fertilizer). The differences were largely attributed to fossil fuel as shown in Table 4.

Ethanol life cycle energy is distributed within three main steps: feedstock production, fuel production, and vehicle operation. For E85s, about 21, 38.3, and 40.7% of energy is used on feedstock production, fuel production, and vehicle operation, respectively. For low blend (E10), the distribution changes to 5.2, 20.4, and 74.4%. In comparison, the life cycle of gasoline is distributed among the three life cycle steps as 6, 13, and 81%. Application of fertilizer increased the share of the energy for feedstock production by 3 and 6% for 56 and 112 kg N ha^{-1}, respectively. The landscape change only led to 1% (higher at the shoulder) difference in the share of energy associated with feedstock production.

Impact of nitrogen fertilizer and landscape position on GHG emissions

The results indicated that the feedstock production lead to a net GHG sink as shown with negative numbers in Table 3. For E85s, 130–160 g km^{-1} of GHG was removed from the atmosphere in nonfertilized switchgrass. But, the addition of fertilizer increased GHG by approximately 69 g km^{-1} and 139 g km^{-1} for 56 and 112 kg N ha^{-1}, respectively. The fuel production also removed a small amount of atmospheric GHG (~3–4 g km^{-1}). However, the GHG sink by the feedstock and fuel production was offset by vehicle operation and resulted into net GHG emissions of about 50–200 g km^{-1}. The landscape position also impacted GHG trends in fertilized plots. For E85s, an average of 18 g km^{-1} more GHGs was removed at the footslope in comparison with the shoulder position (Table 4). In comparison with gasoline, net GHG associated with E85s was between 33 and 82% lower for 56 and 112 kg N ha^{-1}, respectively. For E10, these were 2.8 to 7% lower.

Among individual GHGs, the CO_2 was reduced by the feedstock and fuel production steps for switchgrass ethanol used in E85s. Other GHGs, CH_4 and N_2O, were emitted by all steps of the fuel life cycle and increased with nitrogen rate and at the shoulder position (Fig. 4). N_2O was the GHG that increased the most with the increase in fertilizer rate. N_2O increased approximately 18- and 36-fold for 56 and 112 kg N ha^{-1} fertilizer application, respectively, when the feedstock was produced for E85s. But that increase was about 4.8- to 8.7-folds if the total N_2O from all life cycle steps were considered. For similar situations (adding 56 and 112 kg N ha^{-1}), CH_4 increased by about 73–148%. The N_2O emissions at the shoulder of fertilized plots were 35% higher in comparison with the footslope for E85s. In comparison with gasoline, N_2O emissions were between 540 and 2321% higher for E85s as shown in Fig. 5. For E10, the increase was about 50–200%.

Impact of nitrogen fertilizer and landscape position on volatile organic carbon (VOC) emissions

The results show that increase in fertilization rate to grow switchgrass is associated with increases in VOCs. Although the largest portion of VOCs originated from fuel production (37% for E10, 53% for E85) and vehicle operation (55% for E10, 33% for E85), the fertilizer increase led to increase in total VOCs (14% at 56 kg N ha^{-1}, 27% at 112 kg N ha^{-1}). This increase is most noticeable for E85 fuels, especially at the feedstock production stage where the highest fertilizer rate resulted in approximately 9 times higher VOCs in comparison with no fertilization (Table 3). In comparison with gasoline, the life cycle VOCs for E85 produced from switchgrass grown with no nitrogen were 23% higher than VOCs from gasoline. This percentage increased (by 39% at 56 kg N ha^{-1}, 55% at 112 kg N ha^{-1}) with increases in fertilization rate (Fig. 2). Life cycle VOC emissions from using blended ethanol produced from unfertilized switchgrass grown at the

Table 3 Energy and emissions from different fuels and sources as impacted by N rate; the number in middle brackets in italics is change due to increase of N rate to 56 kg ha^{-1} and the number in the following (last) bracket is increase due 112 kg per ha N rate

Fuel type	Feedstock	Fuel	Vehicle	Fuel type	Feedstock	Fuel	Vehicle
Total E (KJ km^{-1})				Net GHG (g km^{-1})			
Gasoline	230	499	3070	Gasoline	25.8	39.8	224.9
E10	215	841 (*28*) (56)	3070	E10	9.59	36 (*6*) (12)	224.5
FFV-E85	1585 (*314*) (641)	2893	3070	FFV-E85	−160 (*69*) (139)	−3.84 (*0.04*) (0.08)	220.6
Dedi E85	1481 (*294*) (599)	2704	2869	Dedi E85	−150 (*65*) (130)	−3.57 (*0.06*) (0.10)	206.2
CO_2 (g km^{-1})				CH_4 (g km^{-1})			
Gasoline	19	38	223	Gasoline	0.276	0.068	0.007
E10	3	33 (3) (5)	223	E10	0.257	0.066 (*0.005*) (0.010)	0.007
FFV-E85	−164 (*25*) (51)	−12	219	FFV-E85	0.083 (*0.061*) (0.123)	0.026	0.007
Dedi E85	−153 (*23*) (47)	−11	205	Dedi E85	0.078 (*0.057*) (0.115)	0.024	0.007
Net GHG (g km^{-1}) 1 year-harvest				Fossil E (KJ km^{-1})			
Gasoline	25.8	39.8	224.9	Gasoline	218	490	3070
E10	9.59	37.5 (*5.6*) (11.7)	224.5	E10	203	464 (*27*) (55)	2865
FFV-E85	−144 (*65*) (134)	−3.85 (*0.04*) (0.08)	220.6	FFV-E85	223 (*310*) (633)	12	717
Dedi E85	−134 (*60*) (125)	−3.60 (*0.04*) (0.08)	206.2	Dedi E85	208 (*290*) (592)	11	670
VOC (g km^{-1})				CO (g km^{-1})			
Gasoline	0.01	0.068	0.106	Gasoline	0.016	0.059	1.781
E10	0.01	0.074 (*0.002*) (0.005)	0.106	E10	0.015	0.072 (*0.003*) (0.007)	1.781
FFV-E85	0.008 (*0.032*) (0.064)	0.127	0.1	FFV-E85	0.027 (*0.043*) (0.076)	0.193	1.781
Dedi E85	0.008 (*0.029*) (0.060)	0.118	0.1	Dedi E85	0.025 (*0.031*) (0.071)	0.180	1.781
NOx (g km^{-1})				PM10 (g km^{-1})			
Gasoline	0.077	0.055	0.075	Gasoline	0.005	0.048	0.016
E10	0.072	0.076 (*0.009*) (0.020)	0.075	E10	0.005	0.049	0.016
FFV-E85	0.081 (*0.113*) (0.231)	0.224	0.075	FFV-E85	0.006 (*0.007*) (0.015)	0.054	0.016
Dedi E85	0.075 (*0.107*) (0.217)	0.209	0.075	Dedi E85	0.005 (*0.007*) (0.015)	0.050	0.016
PM2.5 (g km^{-1})				SOx (g km^{-1})			
Gasoline	0.005	0.045	0.007	Gasoline	0.033	0.043	0.004
E10	0.004	0.044	0.007	E10	0.031	0.042	0.003
FFV-E85	0.005 (*0.006*) (0.012)	0.024	0.007	FFV-E85	0.022 (*0.101*) (0.207)	0.020	0.002
Dedi E85	0.005 (*0.005*) (0.011)	0.023	0.007	Dedi E85	0.020 (*0.095*) (0.194)	0.019	0.002

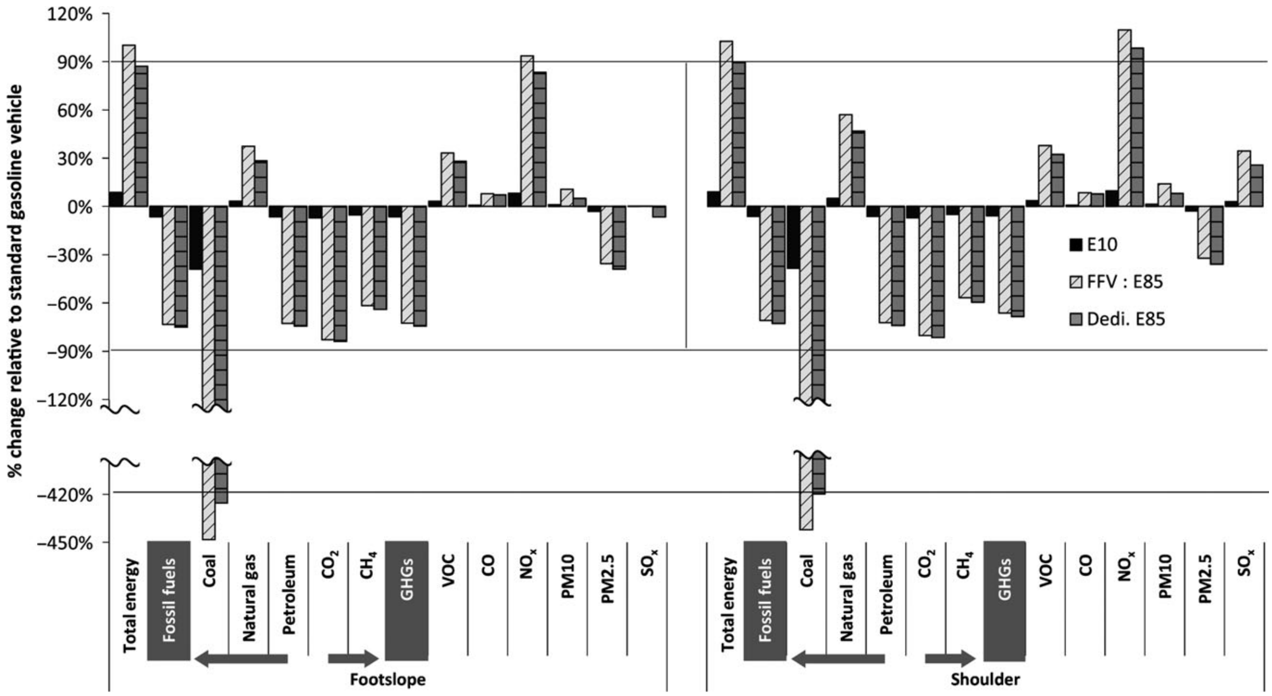

Fig. 3 Impact of landscape on percent change of switchgrass ethanol life cycle impacts relative to gasoline: switchgrass grown with 112 kg N ha^{-1}.

shoulder are similar to those grown at the footslope. In contrast, for plots where 112 kg N ha^{-1} of fertilizer was applied, the E85 life cycle's VOCs were higher (~by 3.5%) for shoulder biomass compared to the footslope biomass. If only VOCs from feedstock production are compared, the shoulder biomass accounts for 45% more VOCs than the footslope. For E10, there was little difference between shoulder and footslope (Table 4).

In comparison with gasoline, E85s (FFV, Dedi.E85, respectively) were linked to approximately 28–38% more VOCs those from gasoline. Life cycle VOCs were slightly higher (by ~3.6%) for E10 than gasoline.

Impact of nitrogen fertilizer and landscape position on criterial pollutants emissions

Carbon monoxide (CO). CO emissions are mainly attributable to vehicle operation (~97%) as shown in Table 3. Hence, the application of fertilizer had a small impact on the life cycle CO; it increased by about 1.7 and 3.6% for addition of 56 and 112 kg N ha^{-1}, respectively, for E85s. However, if only the feedstock production is considered, the increase in CO emissions due to nitrogen application was about 2.2 and 3.8 times higher for E85 with the application of 56 and 112 kg N ha^{-1}, respectively, in comparison with no nitrogen application. In general, the entire life cycle of ethanol–gasoline mix produced approximately 2 g of CO emissions per km. In comparison with gasoline, these emissions were higher by about 7, 8.7, and 10.5% for 0, 56, and 112 kg-N ha^{-1}, respectively. The results also indicated that there were small differences in CO emissions based on landscape positioning. Vehicle operation is the primary source of CO.

NO_x. The results showed that in plots where no fertilizer was applied, the majority of NO_x originated from E85 fuel production (~59%) and the rest of NO_x generated from feedstock production (~21%) and vehicle operation (~10%) (Table 3). The addition of fertilizer changed the distribution of NOx among life cycle steps. For high fertilizer rate, the majority (51%) of NO_x were produced from feedstock production meant for E85s and the fuel production share reduced to ~37%. For gasoline and E10, NO_x were approximately distributed equally on the three life cycle steps. Overall, the life cycle of ethanol–gasoline produced between 252 and 724 mg km^{-1} of NO_x for E10 and E85s, respectively. In comparison with gasoline, these emissions were much higher by about 73.4, 124.5, and 177.5% for 0, 56, and 112 kg-N ha^{-1} fertilization, respectively (Fig. 2).

Results also indicated that the life cycle NO_x emissions were approximately similar for blended fuels derived from the shoulder biomass and footslope biomass on plots with no fertilizer application. For fertilized plots, the footslope biomass (for E85 fuel) was

 GCB Bioenergy, doi: 10.1111/gcbb.12296

Table 4 Energy and emissions from different fuels as impacted by position: the numbers without brackets are for the shoulder and numbers in brackets is the difference between footslope and shoulder

N rate	Fuel type	Feedstock	Fuel	Vehicle	N rate	Fuel type	Feedstock	Fuel	Vehicle
Total E (KJ km^{-1})					Net GHG (g km^{-1})				
0 kg ha^{-1}	Gasoline	230	499	3070	0 kg ha^{-1}	Gasoline	25.8	39.8	224.9
	E10	215	836 (−0.28)	3070		E10	9.6	35.7	224.5
	FFV-E85	1523 (−3.31)	2893	3070		FFV-E85	−164 (−0.25)	−3.8	220.6
	Dedi E85	1424 (−3.09)	2704	2869		Dedi E85	−154 (−0.24)	−3.6	206.2
112 kg ha^{-1}	Gasoline	230	499	3070	112 kg ha^{-1}	Gasoline	25.8	39.8	224.9
	E10	215	854 (−8)	3070		E10	9.6	39.7 (−1.6)	224.5
	FFV-E85	1735 (−94)	2893	3070		FFV-E85	−118.6 (−18.6)	−3.9	220.6
	Dedi E85	1622 (−88)	2704	2869		Dedi E85	−110.9 (−17.4)	−3.6	206.2
CO_2 (g km^{-1})					CH_4 (g km^{-1})				
0 kg ha^{-1}	Gasoline	18.9	37.8	223.5	0 kg ha^{-1}	Gasoline	0.276	0.068	0.007
	E10	3.1	33.0	223.1		E10	0.257	0.065	0.007
	FFV-E85	−169 (−0.25)	−11.8	219.2		FFV-E85	0.077	0.026	0.007
	Dedi E85	−158 (−0.24)	−11.0	204.8		Dedi E85	0.072	0.024	0.007
112 kg ha^{-1}	Gasoline	18.9	37.8	223.4	112 kg ha^{-1}	Gasoline	0.276	0.068	0.007
	E10	3.1	34.0 (−0.7)	223.1		E10	0.257	0.069 (−0.002)	0.007
	FFV-E85	−152 (−7.3)	−11.8	219.2		FFV-E85	0.118 (−0.016)	0.026	0.007
	Dedi E85	−142 (−6.9)	−11.0	204.8		Dedi E85	0.111 (−0.016)	0.024	0.007
N_2O (g km^{-1})					Fossil E (KJ km^{-1})				
0 kg ha^{-1}	Gasoline	0.000	0.001	0.004	0 kg ha^{-1}	Gasoline	218	490	3070
	E10	0.000	0.004	0.004		E10	203	457 (−0.28)	2865
	FFV-E85	0.008	0.025	0.004		FFV-E85	163 (−3.21)	12	717
	Dedi E85	0.008	0.023	0.004		Dedi E85	152 (−3.01)	11	670
112 kg ha^{-1}	Gasoline	0.000	0.001	0.004	112 kg ha^{-1}	Gasoline	218	490	3070
	E10	0.000	0.012 (−0.003)	0.004		E10	203	477 (−8)	2865
	FFV-E85	0.102 (−0.036)	0.024	0.004		FFV-E85	372 (−92)	12	717
	Dedi E85	0.095 (−0.034)	0.023	0.004		Dedi E85	348 (−87)	11	670
VOC (g km^{-1})					CO (g km^{-1})				
0 kg ha^{-1}	Gasoline	0.010	0.068	0.106	0 kg ha^{-1}	Gasoline	0.016	0.059	1.781
	E10	0.010	0.074	0.106		E10	0.015	0.071	1.781
	FFV-E85	0.006	0.127	0.100		FFV-E85	0.017	0.193	1.781
	Dedi E85	0.006	0.118	0.100		Dedi E85	0.016	0.180	1.781
112 kg ha^{-1}	Gasoline	0.010	0.068	0.106	112 kg ha^{-1}	Gasoline	0.016	0.059	1.781
	E10	0.010	0.075	0.106		E10	0.015	0.073	1.781
	FFV-E85	0.027 (−0.008)	0.127	0.100		FFV-E85	0.040 (−0.011)	0.193	1.781
	Dedi E85	0.026 (−0.008)	0.118	0.100		Dedi E85	0.034 (−0.011)	0.180	1.781
NOx (g km^{-1})					PM10 (g km^{-1})				

(continued)

Table 4 (continued)

N rate	Fuel type	Feedstock	Fuel	Vehicle	N rate	Fuel type	Feedstock	Fuel	Vehicle
0 kg ha^{-1}	Gasoline	0.077	0.055	0.075	0 kg ha^{-1}	Gasoline	0.005	0.048	0.016
	E10	0.072	0.074	0.075		E10	0.005	0.048	0.016
	FFV-E85	0.059	0.224	0.075		FFV-E85	0.004	0.054	0.016
	Dedi E85	0.056	0.209	0.075		Dedi E85	0.004	0.050	0.016
112 kg ha^{-1}	Gasoline	0.077	0.055	0.075	112 kg ha^{-1}	Gasoline	0.005	0.048	0.016
	E10	0.072	0.080 (−0.003)	0.075		E10	0.005	0.049	0.016
	FFV-E85	0.136 (−0.033)	0.224	0.075		FFV-E85	0.009 (−0.002)	0.054	0.016
	Dedi E85	0.127 (−0.031)	0.209	0.075		Dedi E85	0.008 (−0.002)	0.050	0.016
PM2.5 (g km^{-1})					SOx (g km^{-1})				
0 kg ha^{-1}	Gasoline	0.005	0.045	0.007	0 kg ha^{-1}	Gasoline	0.033	0.043	0.004
	E10	0.004	0.044	0.007		E10	0.031	0.042	0.003
	FFV-E85	0.003	0.024	0.007		FFV-E85	0.014	0.020	0.002
	Dedi E85	0.003	0.023	0.007		Dedi E85	0.013	0.019	0.002
112 kg ha^{-1}	Gasoline	0.005	0.045	0.007	112 kg ha^{-1}	Gasoline	0.033	0.043	0.004
	E10	0.004	0.044	0.007		E10	0.031	0.050 (−0.003)	0.003
	FFV-E85	0.007 (−0.002)	0.024	0.007		FFV-E85	0.085 (−0.027)	0.020	0.002
	Dedi E85	0.007 (−0.002)	0.023	0.007		Dedi E85	0.080 (−0.026)	0.019	0.002

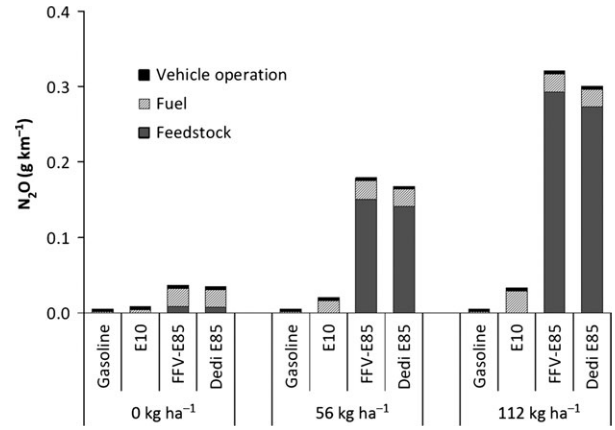

Fig. 4 Impact of nitrogen fertilization rate on life cycle nitrous oxide (N_2O) emissions for four types of fuels subdivided based on life cycle stage (i.e. vehicle operation, fuel or feedstock production).

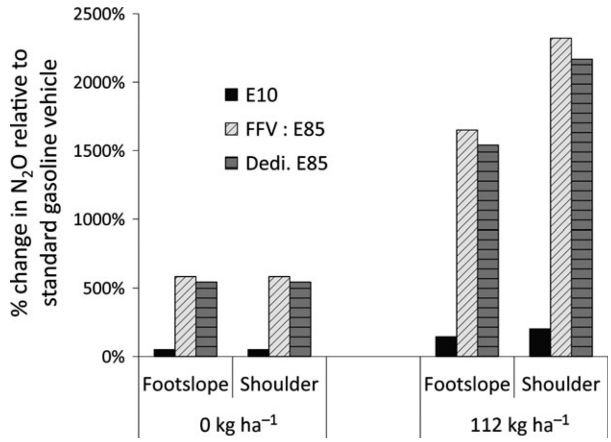

Fig. 5 Impact of landscape position and fertilization on percent change of switchgrass ethanol life cycle nitrous oxide (N_2O) relative to gasoline.

linked to lower (by approximately 8.4%) NO_x compared to the shoulder biomass (Table 4).

SO_x. The largest part of SO_x was contributed by the feedstock (~50%) and fuel production (~45%) for unfertilized plots. Addition of fertilizer increased the feedstock production share (85% for 56 kg N ha^{-1}; 91% for 112 kg N ha^{-1}) in SO_x emissions for E85s. The low ethanol blend (E10) and gasoline life cycle's SO_x emissions were almost similar as shown in Table 3. Vehicle operation contributed only between 0.8 and 4.5% for all fuels. In total, the life cycle of ethanol–gasoline mix produced between 23 and 251 mg of SO_x per km with the highest amount linked to highest N rate. In comparison with gasoline, SO_x emissions were lower (~54%) for

ethanol–gasoline mix produced from switchgrass that did not receive the fertilizer. However, there was a reversal when fertilizer was applied for E85, it led to 82 and 215% higher SO_x emissions, for 56 and 112 kg N ha^{-1}, respectively. Landscape positioning also impacted the life cycle SO_x emissions. Lower emissions (by approximately 35%) for E85 from footslope biomass in comparison with shoulder biomass were observed in plots that received 112 kg N ha^{-1}. Results indicated that life cycle SO_x emissions from shoulder biomass (used in E85) were higher than gasoline's emissions (Table 4), whereas SO_x emissions from the footslope biomass were approximately equal to emissions from gasoline (Fig. 3).

PM10 and PM2.5. The results indicated that the majority (50 to 79%) of the particulate matters are emitted during fuel production for both gasoline and ethanol–gasoline mix (Table 3). PM10 emissions from vehicle operation are more than three times higher than those from feedstock production, whereas PM2.5 emissions from vehicle operation are close to those from feedstock production. The application of 56 kg N ha^{-1} of fertilizer more than doubled feedstock production PMx emissions, and the application of 112 kg N ha^{-1} more than tripled feedstock PM emissions for E85 fuels. The results also showed that the life cycle of blended ethanol produced between 69 and 90 mg·PM10 km^{-1}, whereas it produced between 34 and 56 mg·PM2.5 km^{-1}. In comparison with gasoline (Fig. 2), PM10 from FFV:E85 was higher (by 4% for low N rate to 32% for high N rate), whereas those from PM2.5 were lower (by 15% for low N rate to 54% for high N rate). Further, the results indicated that field positioning on unfertilized plots did not impact life cycle PM. However, the addition of fertilizer increased PM10 by 3% for E85 from switchgrass grown at the shoulder in comparison with the footslope. Similarly, PM2.5 was 5% higher for E85 from switchgrass grown at the shoulder.

Impact of producing switchgrass for a period shorter than maximum stand life

In case the switchgrass is abandoned after only one harvest, this scenario would result in 2 to 3% more life cycle energy use, 20% more fossil fuel use in unfertilized plots and 8 to 12% more fossil fuels in fertilizer plots. It would also lead to 10 to 14% increase in life cycle PM from biomass grown in unfertilized plots and 4 to 9% for fertilized plots. No significant changes in N_2O and VOCs changes would be observed from shorting the stand life. The highest change would occur to life cycle SOx, with an increase of about 44% for unfertilized plots and 6 to 11% for fertilizer plots. The life cycle environmental impacts due to shortening the stand life to one year were largely attributed to the feedstock production step.

Discussion

This discussion will explain the impact of nitrogen rate and landscape positions on emissions and energy use from ethanol-blend life cycle in the context of previous studies. However, it will not attempt to explain the source of all emissions and energy. This information can be obtained from the GREET tool database (downloadable from https://greet.es.anl.gov/), and it explains mass (including emissions) and energy flows from production of agricultural inputs, production of chemicals, and additives involved in ethanol (and other fuels involved such as petroleum, natural gas, coal) production, ethanol conversion and purification processes, and transportation.

Energy and emissions from switchgrass feedstock production constitute a key portion of the switchgrass-derived blended ethanol life cycle. These findings were consistent with previous studies: In Wang *et al.* (2012), a well-to-wheel analysis using GREET model showed that the GHG emissions from feedstock production were approximately half of the total GHG emissions for switchgrass-derived ethanol. Approximately 57–110% of GHG reductions with respect to gasoline were computed using GHGenius model (well to wheels) by Spatari *et al.* (2005), EBAMM model (well to pump) by Schmer *et al.* (2008), and GREET model (well to wheels) by Wu *et al.* (2006) and Wang *et al.* (2012). Fossil fuel replacement and other emissions in this study were also in line with findings in Wu *et al.* (2006) and Wang *et al.* (2012); Wu *et al.* (2006)'s GREET simulations. However, parameterization differences were discovered in some studies, for example, estimates of biomass yield and land-use change-related carbon sequestration in this study were conservative in comparison with Cherubini & Jungmeier (2010) who estimated 3 times higher yields and carbon sequestration. This variability was addressed by studies that conducted stochastic analysis of variables [e.g., Spatari & MacLean (2010)] and indicated that CO_2 emissions due land-use change and N_2O due to fertilizers are major source of uncertainty in LCA of cellulosic ethanol.

It is important to explore the impact of nitrogen fertilizer rate on switchgrass because it leads to increase in yield but adversely contributes to generation of emissions (N_2O, CO_2, NO_x) and increased energy use. Previous researchers doubted the environmental benefits of producing biofuel from plants that require fertilizers (Searchinger *et al.*, 2008). It is believed that N_2O emitted from soil due to nitrogen addition could offset

the benefits of biofuels. But, land where no fertilizer was added also emitted N_2O due to natural cycling of nitrogen in soil, water, and the atmosphere (Vitousek *et al.*, 1997). Under anaerobic conditions, nitrogen in soil is transformed by microbes into N_2O (Smith *et al.*, 2008). This study demonstrated that increase in N_2O emissions is primarily offset by CO_2 taken up from the atmosphere to grow biomass and subsequently the biomass stored in the soil (roots) replenishes soil carbon. Croplands converted to grasslands (such as switchgrass) significantly improve soil carbon (Fazio & Monti, 2011).

The addition of regionally optimized N fertilization (56 kg N ha^{-1} for SD) during switchgrass production is likely economical; 37% more blended ethanol was generated with the same land than with unfertilized. Overfertilization (112 kg N ha^{-1} in this study) has no economic benefits and causes adverse environmental impacts. Field testing of soil nutrients (N, P, K, and S) and acidity can further reduce inputs, costs, and enhance yield during switchgrass production. Previous switchgrass LCA studies included addition of K, P, and lime and found these to add to the increase in energy use and emissions (Wu *et al.*, 2006; Bai *et al.*, 2010). In this study, K, P, S, and lime were not added because preliminary soil tests determined that it was not necessary. For high ratio of switchgrass ethanol fuel blends (E85), N optimization can improve GHGs, VOCs, NO_x, SO_x, and PM which are heavily generated from feedstock production. Overfertilization (112 kg N ha^{-1}) reduced life cycle environmental benefits almost by half or doubled the adverse impacts for switch-derived ethanol. Feedstock production involves more modeling uncertainty due to spatial variability in soils and climate, agricultural management, and the complex cycle of nitrogen and carbon at the farm level. The number of harvests before the switchgrass is replanted influences life cycle impacts, that is, the more years of productivity a stand provides, the greater the environmental benefits. Most previous studies indicate that switchgrass stands last between 10 and 20 years; however, stand duration depends on crop condition, marketability, and management decisions. Results demonstrated that, even with only one year of harvest, the switchgrass-derived ethanol would be better than gasoline in term of fossil fuel use, GHGs, and PM2.5. In other categories such as VOCs, CO, PM10, and NO_x, total energy gasoline is better than E85s for one year of harvest. This study showed that as a perennial crop, switchgrass has the benefit, once established (1–3 years), of avoiding energy use and pollution from planting and pesticides application, production of pesticides, and disruption of carbon sequestration.

Although using blended ethanol resulted in net GHG emissions, the primary goal is to develop renewable fuel sources better than existing nonrenewable fuels (e.g., gasoline). This study showed that GHGs were significantly reduced for switchgrass-derived E85 compared to gasoline. Agricultural management significantly influences switchgrass-based ethanol life cycle. Over the years, the emphasis was placed on making passenger vehicle more efficient to reduce emissions. However, increasing agricultural machinery efficiency can have a significant impact on emissions and fuel use reductions. For instance, Bochtis *et al.* (2010) showed that controlled traffic at the farm can itself significantly increase efficiency.

Landscape positioning where switchgrass is grown could have a significant impact on the life cycle of switchgrass-derived ethanol. Erosion and drainage from high elevation (shoulder) to low elevation (footslope) causes higher biomass growth at low elevation position due to higher moisture, nutrients, and organic matter (Mbonimpa *et al.*, 2015). The LCA in this study demonstrated that the footslope is linked to lower switchgrass-derived ethanol GHGs due to primarily higher biomass growth (CO_2 uptake) compared to the shoulder. Moreover, the analysis showed that the footslope was, in general, linked to better energy use and fewer emissions compared to the shoulder due to increased productivity. The increased productivity within the fertilized switchgrass appears likely due to downslope transport of fertilizer and soil rich in organic matter (erosion) from shoulder to the footslope.

Presently, corn ethanol dominates the US market for ethanol–gasoline blends and it is important to have a perspective on how switchgrass ethanol (cellulosic) compares to corn ethanol (starch). Using well-to-wheels GREET model simulations, Wang *et al.* (2012) and Wu *et al.* (2006) conducted simulations that compared life cycle impacts from corn ethanol, switchgrass ethanol, and gasoline (per unit joules contained in the fuel or on basis of using it in flex fuel vehicles-E85s). They indicated that when corn ethanol and switchgrass ethanol are compared to gasoline, switchgrass displaces about 57–66% of fossil fuels and 62–97% of GHGs whereas corn ethanol displaces about 32–57% of fossil fuels and 19–48% of GHGs. In comparison with gasoline, switchgrass ethanol produces 40% higher amount of NOx while corn ethanol produces 100% higher NOx. switchgrass ethanol showed benefits in reducing PM10 (by 30%) and SOx (by 40%) while corn ethanol contributed higher amount of PM 10 (>200%) and SOx (105%) in comparison with gasoline. Corn ethanol also had slightly higher amount of VOCs and CO. They attributed these differences to

this fact: 'Instead of using coal or natural gas to fuel the ethanol plant, as in the corn ethanol production process, the conversion process in their study (similar to our study) relies on biomass residuals and methane gas from an on-site waste water treatment plant to generate heat and power, which decreases fossil energy consumption' (Wu *et al*., 2006).

Although this study did not analyze other environmental impacts such as eutrophication and ecotoxicity potential, it is expected that these impacts can be reduced when a cropland is converted into a perennial grassland (Monti *et al*., 2009). In addition, perennial grasses such as switchgrass improve the biodiversity of species in the area (Hartman *et al*., 2011). While GREET is an efficient, effective model to analyze the life cycle of switchgrass fuel systems, it is a simplification of a complex system that would be strongly linked to policy and market effects (Stratton *et al*., 2011). In the future, better understanding of switchgrass systems should be realized when mass commercialization of switchgrass-derived is further established.

In conclusion, generation and use of switchgrass ethanol–gasoline mixture can displace GHGs emissions. It can also lead to displacement of total fossil fuels because petroleum and coal reductions offset observed increase in natural gas. The increase in natural gas was mainly contributed by fertilizer application. Therefore, overfertilization should be avoided (e.g., rate above 56 kg N ha^{-1} in this case) because fertilizers-related energy and emissions are a significant portion of the entire switchgrass ethanol life cycle. There is also a difficulty to generalize the benefits or drawbacks of switchgrass ethanol due to the impact other environmental conditions such as landscape topography can have on switchgrass ethanol life cycle. Better soil conditions at the footslope of the hill, where eroded material deposited, led to greater life cycle environmental benefits. Selective topography-based planting of switchgrass in footslopes, such as riparian corridors, may be both economically and environmentally favorable. However, it is believed that in the long-term switchgrass could improve the soil quality at eroded higher grounds as well. For a future follow-up study, we recommend LCA for switchgrass from various geographical locations, ethanol produced using other process pathways, and exploration of other environmental impact categories.

Acknowledgements

This study was supported by the North Central Regional Sun Grant Center at South Dakota State University (SDSU) through a grant provided by the US Department of Energy Bioenergy Technologies Office under award number DE-FC36-05GO85041.

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